PRESSURE PROBE

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0001] The invention relates to industrial equipment. More particularly, the invention relates to the detonative cleaning of industrial equipment.

(2) Description of the Related Art

[0002] Surface fouling is a major problem in industrial equipment. Such equipment includes furnaces (coal, oil, waste, etc.), boilers, gasifiers, reactors, heat exchangers, and the like. Typically the equipment involves a vessel containing internal heat transfer surfaces that are subjected to fouling by accumulating particulate such as soot, ash, minerals and other products and byproducts of combustion, more integrated buildup such as slag and/or fouling, and the like. Such particulate build-up may progressively interfere with plant operation, reducing efficiency and throughput and potentially causing damage. Cleaning of the equipment is therefore highly desirable and is attended by a number of relevant considerations. Often direct access to the fouled surfaces is difficult. Additionally, to maintain revenue it is desirable to minimize industrial equipment downtime and related costs associated with cleaning. A variety of technologies have been proposed. By way of example, various technologies have been proposed in U.S. patents 5,494,004 and 6,438,191 and U.S. patent application publication 2002/0112638. Additional technology is disclosed in Huque, Z. Experimental Investigation of Slag Removal Using Pulse Detonation Wave Technique, DOE/HBCU/OMI Annual Symposium, Miami, FL., March 16-18, 1999. Particular blast wave techniques are described by Hanjalić and Smajević in their publications: Hanjalić, K. and Smajević, I., Further Experience Using Detonation Waves for Cleaning Boiler Heating Surfaces, International Journal of Energy Research Vol. 17, 583-595 (1993) and Hanjalić, K. and Smajević, I., Detonation-Wave Technique for On-load Deposit Removal from Surfaces Exposed to Fouling: Parts I and II, Journal of Engineering for Gas Turbines and Power, Transactions of the ASME, Vol. 1, 116 223-236, January 1994. Such systems are also discussed in Yugoslav patent publications P 1756/88 and P 1728/88. Such systems are often identified as "soot blowers" after an exemplary application for the technology.

[0003] Nevertheless, there remain opportunities for further improvement in the field.

SUMMARY OF THE INVENTION

[0004] Accordingly, one aspect of the invention involves an apparatus for cleaning a surface within a vessel. A vessel wall separates a vessel exterior from a vessel interior and has a wall aperture. The apparatus includes an elongate conduit having an upstream first and a downstream second end and positioned to direct a shockwave from the second end into the vessel interior. A pressure probe includes a body held in an operative position within the vessel so as to be exposed to the shockwave after the shockwave exits the conduit second end. The body has an exterior surface with a convergent nose portion. There is a first port in the body. A passageway extends between the first port and a pressure sensor. A support member holds the body in the operative position.

[0005] In various implementations, the probe may further include a cooling fluid circuit at least partially through the support member and body. The support member may include a cooling liquid-carrying conduit joining the body from above. The cooling liquid-carrying conduit may extend through the vessel wall. A source of fuel and oxidizer may be coupled to the conduit to deliver the fuel and oxidizer to the conduit. An initiator may be positioned to initiate a reaction of the fuel and oxidizer to produce the shockwave.

[0006] Another aspect of the invention involves a pressure probe apparatus with a body having an exterior surface with a forwardly-convergent nose portion. A passageway extends between a first port in the body and a pressure sensor. A support member holds the body in an operative position. A cooling fluid circuit extends at least partially through the support member and body.

[0007] In various implementations, the cooling circuit may extend around a periphery of a conduit defining the passageway. The body may have an aft surface with a second port and the cooling circuit may extend through the second port. The first port may be on a flat. The aft surface may have a third port and the cooling circuit may bifurcate so as to extend through the second and third ports. The apparatus may be combined with a cooling liquid flow in the cooling circuit. The support may carry a signal communication line from the pressure sensor. The nose may extend for at least 50% of a body length. Along at least 50% of a nose length, the nose may essentially converge forwardly with a half angle between 5° and 15°. The cooling circuit may span, within the body, at least 50% of the body length. An exemplary body length is between 2cm and 20cm and an exemplary maximum transverse dimension is no more than 4cm. The apparatus may be used in combination with a detonative cleaning apparatus.

[0008] Another aspect of the invention involves a method for cleaning a surface within a vessel. Fuel and oxidizer are introduced to a conduit. A reaction of the fuel and oxidizer is initiated so as to cause a shockwave to impinge upon the surface. A pressure probe is used within the vessel to measure a pressure magnitude of the shockwave.

[0009] In various implementations, the method may be performed in a repeated sequential way. The reaction may include a deflagration-to-detonation transition. A cooling fluid may be passed through the pressure probe. The pressure probe may be repositioned by acting upon a support portion of a probe support member outside of the vessel.

[0010] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a view of an industrial furnace associated with several soot blowers positioned to clean a level of the furnace.

[0012] FIG. 2 is a side view of one of the blowers of FIG. 1.

[0013] FIG. 3 is a partially cut-away side view of an upstream end of the blower of FIG. 2.

[0014] FIG. 4 is a longitudinal sectional view of a main combustor segment of the soot blower of FIG. 2.

[0015] FIG. 5 is an end view of the segment of FIG. 4.

[0016] FIG. 6 is a partial side view of a pressure probe assembly associated with the outlet end of a combustion conduit.

[0017] FIG. 7 is a partial longitudinal sectional view of a probe unit of the assembly of FIG. 6.

[0018] FIG. 8 is an aft end view of the probe unit of FIG. 7.

[0019] FIG. 9 is a view of a pressure probe mounting bracket.

[0020] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0021] FIG. 1 shows a furnace 20 having an exemplary three associated soot blowers 22. In the illustrated embodiment, the furnace vessel is formed as a right parallelepiped and the soot blowers are all associated with a single common wall 24 of the vessel and are positioned at like height along the wall. Other configurations are possible (e.g., a single soot blower, one or more soot blowers on each of multiple levels, and the like).

[0022] Each soot blower 22 includes an elongate combustion conduit 26 extending from an upstream distal end 28 away from the furnace wall 24 to a downstream proximal end 30 closely associated with the wall 24. Optionally, however, the end 30 may be well within the furnace. In operation of each soot blower, combustion of a fuel/oxidizer mixture within the conduit 26 is initiated proximate the upstream end (e.g., within an upstreammost 10% of a conduit length) to produce a detonation wave which is expelled from the downstream end as a shockwave along with associated combustion gases for cleaning surfaces within the interior volume of the furnace. Each soot blower may be associated with a fuel/oxidizer source 32. Such source or one or more components thereof may be shared amongst the various soot blowers. An exemplary source includes a liquefied or compressed gaseous fuel cylinder 34 and an oxygen cylinder 36 in respective containment structures 38 and 40. In the exemplary embodiment, the oxidizer is a first oxidizer such as essentially pure oxygen. A second oxidizer may be in the form of shop air delivered from a central air source 42. In the exemplary embodiment, air is stored in an air accumulator 44. Fuel, expanded from that in the cylinder 34 is generally stored in a fuel accumulator 46. Each exemplary source 32 is coupled to the associated conduit 26 by appropriate plumbing below. Similarly, each soot blower includes a spark box 50 for initiating combustion of the fuel oxidizer mixture and which, along with the source 32, is controlled by a control and monitoring system (not shown). FIG. 1 further shows the wall 24 as including a number of ports for inspection and/or measurement. Exemplary ports include an optical monitoring port 54 and a temperature monitoring port 56 associated with each soot blower 22 for respectively receiving an infrared and/or visible light video camera and thermocouple probe for viewing the surfaces to be cleaned and monitoring internal temperatures. Other probes/monitoring/sampling may be utilized, including pressure monitoring, composition sampling, and the like.

[0023] FIG. 2 shows further details of an exemplary soot blower 22. The exemplary detonation conduit 26 is formed with a main body portion formed by a series of doubly flanged conduit sections or segments 60 arrayed from upstream to downstream and a downstream nozzle conduit section or segment 62 having a downstream portion 64 extending

through an aperture 66 in the wall and ending in the downstream end or outlet 30 exposed to the furnace interior 68. The term nozzle is used broadly and does not require the presence of any aerodynamic contraction, expansion, or combination thereof. Exemplary conduit segment material is metallic (e.g., stainless steel). The outlet 30 may be located further within the furnace if appropriate support and cooling are provided. FIG. 2 further shows furnace interior tube bundles 70, the exterior surfaces of which are subject to fouling. In the exemplary embodiment, each of the conduit segments 60 is supported on an associated trolley 72, the wheels of which engage a track system 74 along the facility floor 76. The exemplary track system includes a pair of parallel rails engaging concave peripheral surfaces of the trolley wheels. The exemplary segments 60 are of similar length L_1 and are bolted end-to-end by associated arrays of bolts in the bolt holes of their respective flanges. Similarly, the downstream flange of the downstreammost of the segments 60 is bolted to the upstream flange of the nozzle 62. In the exemplary embodiment, a reaction strap 80 (e.g., cotton or thermally/structurally robust synthetic) in series with one or more metal coil reaction springs 82 is coupled to this last mated flange pair and connects the combustion conduit to an environmental structure such as the furnace wall for resiliently absorbing reaction forces associated with discharging of the soot blower and ensuring correct placement of the combustion conduit for subsequent firings. Optionally, additional damping (not shown) may be provided. The reaction strap/spring combination may be formed as a single length or a loop. In the exemplary embodiment, this combined downstream section has an overall length L_2.

[0024] Extending downstream from the upstream end 28 is a predetonator conduit section/segment 84 which also may be doubly flanged and has a length L_3. The predetonator conduit segment 84 has a characteristic internal cross-sectional area (transverse to an axis/centerline 500 of the conduit) which is smaller than a characteristic internal cross-sectional area (e.g., mean, median, mode, or the like) of the downstream portion (60, 62) of the combustion conduit. In an exemplary embodiment involving circular sectioned conduit segments, the predetonator cross-sectional area is a characterized by a diameter of between 8 cm and 12 cm whereas the downstream portion is characterized by a diameter of between 20 cm and 40 cm. Accordingly, exemplary cross-sectional area ratios of the downstream portion to the predetonator segment are between 1:1 and 10:1, more narrowly, 2:1 and 10:1. An overall length L between ends 28 and 30 may be 1-15 m, more narrowly, 5-15 m. In the exemplary embodiment, a transition conduit segment 86 extends between the predetonator segment 84 and the upstreammost segment 60. The segment 86 has upstream and downstream

flanges sized to mate with the respective flanges of the segments 84 and 60 has an interior surface which provides a smooth transition between the internal cross-sections thereof. The exemplary segment 86 has a length L_4. An exemplary half angle of divergence of the interior surface of segment 86 is ≤ 12°, more narrowly 5-10°.

[0025] A fuel/oxidizer charge may be introduced to the detonation conduit interior in a variety of ways. There may be one or more distinct fuel/oxidizer mixtures. Such mixture(s) may be premixed external to the detonation conduit, or may be mixed at or subsequent to introduction to the conduit. FIG. 3 shows the segments 84 and 86 configured for distinct introduction of two distinct fuel/oxidizer combinations: a predetonator combination; and a main combination. In the exemplary embodiment, in an upstream portion of the segment 84, a pair of predetonator fuel injection conduits 90 are coupled to ports 92 in the segment wall which define fuel injection ports. Similarly, a pair of predetonator oxidizer conduits 94 are coupled to oxidizer inlet ports 96. In the exemplary embodiment, these ports are in the upstream half of the length of the segment 84. In the exemplary embodiment, each of the fuel injection ports 92 is paired with an associated one of the oxidizer ports 96 at even axial position and at an angle (exemplary 90° shown, although other angles including 180° are possible) to provide opposed jet mixing of fuel and oxidizer. Discussed further below, a purge gas conduit 98 is similarly connected to a purge gas port 100 yet further upstream. An end plate 102 bolted to the upstream flange of the segment 84 seals the upstream end of the combustion conduit and passes through an igniter/initiator 106 (e.g., a spark plug) having an operative end 108 in the interior of the segment 84.

[0026] In the exemplary embodiment, the main fuel and oxidizer are introduced to the segment 86. In the illustrated embodiment, main fuel is carried by a number of main fuel conduits 112 and main oxidizer is carried by a number of main oxidizer conduits110, each of which has terminal portions concentrically surrounding an associated one of the fuel conduits 112 so as to mix the main fuel and oxidizer at an associated inlet 114. In exemplary embodiments, the fuels are hydrocarbons. In particular exemplary embodiments, both fuels are the same, drawn from a single fuel source but mixed with distinct oxidizers: essentially pure oxygen for the predetonator mixture; and air for the main mixture. Exemplary fuels useful in such a situation are propane, MAPP gas, or mixtures thereof. Other fuels are possible, including ethylene and liquid fuels (e.g., diesel, kerosene, and jet aviation fuels). The oxidizers can include mixtures such as air/oxygen mixtures of appropriate ratios to achieve desired main and/or predetonator charge chemistries. Further, monopropellant fuels having molecularly combined fuel and oxidizer components may be options.

[0027] In operation, at the beginning of a use cycle, the combustion conduit is initially empty except for the presence of air (or other purge gas). The predetonator fuel and oxidizer are then introduced through the associated ports filling the segment 84 and extending partially into the segment 86 (e.g., to near the midpoint) and advantageously just beyond the main fuel/oxidizer ports. The predetonator fuel and oxidizer flows are then shut off. An exemplary volume filled the predetonator fuel and oxidizer is 1-40%, more narrowly 1-20% of the combustion conduit volume. The main fuel and oxidizer are then introduced, to substantially fill some fraction (e.g., 20-100%) of the remaining volume of the combustor conduit. The main fuel and oxidizer flows are then shut off. The prior introduction of predetonator fuel and oxidizer past the main fuel/oxidizer ports largely eliminates the risk of the formation of an air or other non-combustible slug between the predetonator and main charges. Such a slug could prevent migration of the combustion front between the two charges.

[0028] With the charges introduced, the spark box is triggered to provide a spark discharge of the initiator igniting the predetonator charge. The predetonator charge being selected for very fast combustion chemistry, the initial deflagration quickly transitions to a detonation within the segment 84 and producing a detonation wave. Once such a detonation wave occurs, it is effective to pass through the main charge which might, otherwise, have sufficiently slow chemistry to not detonate within the conduit of its own accord. The wave passes longitudinally downstream and emerges from the downstream end 30 as a shockwave within the furnace interior, impinging upon the surfaces to be cleaned and thermally and mechanically shocking to typically at least loosen the contamination. The wave will be followed by the expulsion of pressurized combustion products from the detonation conduit, the expelled products emerging as a jet from the downstream end 30 and further completing the cleaning process (e.g., removing the loosened material). After or overlapping such venting of combustion products, a purge gas (e.g., air from the same source providing the main oxidizer and/or nitrogen) is introduced through the purge port 100 to drive the final combustion products out and leave the detonation conduit filled with purge gas ready to repeat the cycle (either immediately or at a subsequent regular interval or at a subsequent irregular interval (which may be manually or automatically determined by the control and monitoring system)). Optionally, a baseline flow of the purge gas may be maintained between charge/discharge cycles so as to prevent gas and particulate from the furnace interior from infiltrating upstream and to assist in cooling of the detonation conduit.

[0029] In various implementations, internal surface enhancements may substantially increase internal surface area beyond that provided by the nominally cylindrical and

frustoconical segment interior surfaces. The enhancement may be effective to assist in the deflagration-to-detonation transition or in the maintenance of the detonation wave. FIG. 4 shows internal surface enhancements applied to the interior of one of the main segments 60. The exemplary enhancement is nominally a Chin spiral, although other enhancements such as Shchelkin spirals and Smirnov cavities may be utilized. The spiral is formed by a helical member 120. The exemplary member 120 is formed as a circular-sectioned metallic element (e.g., stainless steel wire) of approximately 8-20mm in sectional diameter. Other sections may alternatively be used. The exemplary member 120 is held spaced-apart from the segment interior surface by a plurality of longitudinal elements 122. The exemplary longitudinal elements are rods of similar section and material to the member 120 and welded thereto and to the interior surface of the associated segment 60. Such enhancements may also be utilized to provide predetonation in lieu of or in addition to the foregoing techniques involving different charges and different combustor cross-sections.

[0030] The apparatus may be used in a wide variety of applications. By way of example, just within a typical coal-fired furnace, the apparatus may be applied to: the pendants or secondary superheaters, the convective pass (primary superheaters and the economizer bundles); air preheaters; selective catalyst removers (SCR) scrubbers; the baghouse or electrostatic precipitator; economizer hoppers; ash or other heat/accumulations whether on heat transfer surfaces or elsewhere, and the like. Similar possibilities exist within other applications including oil-fired furnaces, black liquor recovery boilers, biomass boilers, waste reclamation burners (trash burners), and the like.

[0031] FIG. 6 shows a pressure probe assembly 150 having a head or probe unit 152 positioned facing the outlet 30. In the exemplary embodiment, the probe is positioned in the area swept by the internal cross-section of the combustion conduit outlet in the direction of the centerline 500 and is in relatively close facing proximity (e.g., within 3m of the outlet, more preferably 0.1m-2m). The probe unit 152 is held at the distal end 154 of a support arm 156. As discussed below, the support arm 156 functions not only to support and locate the probe unit but to carry signal and cooling fluid communication for the probe unit. In the exemplary embodiment, the arm 156 is supported by a mounting bracket 158 held relative to some environmental structure (e.g., the furnace wall, or, as illustrated, the combustion conduit such as via the flange joints between the nozzle segment 62 and the segment upstream thereof). The bracket 158 may rigidly locate the arm or may provide for angular and translational excursions of the arm. In the exemplary embodiment, proximate an upstream end 160 of the arm, the arm is provided with port fittings for signal and fluid lines 162 and

164, respectively discussed in further detail below. An exemplary arm length is 2-6m and diameter is 2-5 cm. For pressure monitoring in locations more remote from the nozzle and/or wall aperture, other arm constructions and mounting arrangements may be more appropriate.

[0032] FIG. 7 shows further details of the exemplary probe unit. The unit has a body which may be formed of a material suitable for withstanding expected thermal and mechanical shock stresses. An exemplary body has a main piece 170 which may be machined from a metal (e.g., nickel- or cobalt-based superalloy, stainless steel, or the like). The main piece extends along a nose portion 172 aft from a tip 174. The nose portion has a generally frustoconical surface 176 of half angle θ. Exemplary θ is $\leq 30°$, more narrowly 5°-15°. The nose portion conical, or near conical, shape helps minimize formation of static shocks and the low angle taper helps keep the passing shockwave essentially attached to the body. The nose portion extends aft to an aft portion 178 which has a generally cylindrical external surface 180 provided with a single flat facet 182. The body aft portion has an aft rim 184 secured relative to an aft endplate 186. The body aft portion has a pair of opposed apertures. A first aperture 188 in the facet 182 accommodates a first (outboard) end portion 190 of a conduit 192 extending inboard (i.e., into an interior space 194 of the probe body) to a second (inboard) end portion 196). A second aperture 198 is in the cylindrical surface 180 opposite the aperture 188 and accommodates a support conduit 200. The support conduit 200 may be formed as the distal end portion 154 of the arm 156 or may be secured thereto. Centrally within the conduit 200, a pressure transducer 202 is held within a mounting fixture 204. The fixture 204 extends from an upstream end portion 206 to a downstream end portion 208. The downstream end portion 208 is coupled to the tube inboard end portion 196 to combine to define a flowpath 210 from an inlet 212 at the tube first end 190 to the operative end (e.g., membrane) of the pressure transducer 202. An exemplary length of the flowpath 210 is 0.5-5 cm. The fixture 204 may be supported entirely by its interaction with the tube or may be supported via webs (not shown - e.g., left between longitudinally-drilled holes) extending radially outward to the conduit 200. Overall body size may balance minimizing interference with the shockwave (indicating a small body) with appropriate robustness and economy of manufacture (indicating a potentially larger body). Exemplary body lengths are 2-20 cm and exemplary maximum transverse dimensions (e.g., diameter along the aft portion) are less than 4 cm.

[0033] The signal communication line 162 (e.g., coaxial cable). The line 162 may be connected to a control/monitoring system (not shown). As the length of the flowpath 210 may affect measured pressure values relative to the inlet 212, the control/monitoring subsystem

may be programmed to correct for this (e.g., 1D pressure magnitude attenuation and phase corrections).

[0034] An annular or interrupted annular space 216 between the fixture 204 and conduit 200 accommodates the downstream flow of fluid from the fluid line 164 along fluid flowpaths 218. In the exemplary embodiment, the probe body interior 194 has a series of progressively smaller cross-section areas, one ahead of the other within the nose, to permit the pathway to pass therewithin to cool the nose. In the exemplary embodiment, the endplate 186 has a pair of apertures 220 (FIG. 8) associated with fittings 222 coupled to a coolant return line 224 (FIG. 6) which may be secured relative to the arm 156 such as via hose clamps 226.

[0035] FIG. 9 shows further details of the mounting bracket 158. The exemplary bracket includes a body piece 240 formed as a sector of an annular metallic plate having first and second faces and extending between first and second circumferential ends and inner and outer diameter perimeter portions 242 and 244. Near the inner diameter perimeter portion 242 bolt holes 246 correspond to the pattern of bolt holes of the associated nozzle and downstreammost doubly flanged segment flanges so as to permit the plate to be secured to the flanges by a group of the flange bolts. The outer diameter perimeter portion 244 includes a recess with a base portion 248 complementary to a portion of the cross-section of the arm 156. A remaining portion of the recess is dimensioned to accommodate a clamp body 250 having an inner surface 252 complementary to an opposite portion of the arm cross-section (e.g., to form an approximate circle with the surface 248). Knob-headed bolts 254 may secure the clamp body 250 to the bracket body 240 to permit a secure clamping of the arm between the two to precisely hold the arm in a given position. This permits precise positioning of the probe unit a given distance from the outlet end. Due to an offset of the probe from the clamped length of the arm, the rotational orientation of the arm may be used to position the probe transversely relative to the outlet.

[0036] In operation, the shockwave passes downstream over the nose, and along the body aft portion 178. When the shockwave reaches the port 212, its effects can pass along the path 210 to the pressure transducer that in turn provides an output signal indicative of the pressure magnitude of the shockwave. The probe assembly is initially positioned so that the probe unit is at a predetermined location relative to the combustion tube outlet. This may be performed while the outlet is disengaged from the furnace. Thereafter, the outlet may be inserted into the furnace, and the reaction strap or other restraints installed. The firing process may then be initiated.

[0037] One or more embodiments of the present invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, the invention may be adapted for use with a variety of industrial equipment and with variety of soot blower technologies. Aspects of the existing equipment and technologies may influence aspects of any particular implementation. Accordingly, other embodiments are within the scope of the following claims.